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Effect of spatial hole burning and multi-mode generation threshold in quantum dot lasers

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Abstract. Theoretical analysis of the spatial hole burning in quantum dot (QD) lasers is given. The multi-mode generation threshold is calculated. The processes of the thermally excited escapes of carriers away from QDs are shown to control the multi-mode generation threshold. The dependences of the multi-mode generation threshold on the root mean square of relative QD size fluctuations, cavity length, surface density of QDs, and temperature are obtained.

Introduction

In [1]–[3], theory of threshold current density of a quantum dot (QD) laser and its temperature dependence has been developed having regard to inhomogeneous line broadening caused by the dispersion in QD sizes. The optimum parameters of the laser structure minimizing the threshold current density have been calculated as the functions of the QD size dispersion, total losses, and temperature.

This article discusses the effect of spatial hole burning and multi-mode generation threshold in QD lasers. As in conventional quantum well (QW) or bulk lasers (as well as in solid state lasers) [4, 5], spatial hole burning in QD lasers is due to the non-uniformity of the stimulated recombination of carriers along the longitudinal direction in the waveguide. Due to the fact that, at and above the lasing threshold, the electric field of the emitted light is a standing wave and is a periodic function of the longitudinal coordinate, the stimulated recombination of the carriers will be more intensive in the QDs located at the antinodes of the light intensity, while it will be less intensive in the QDs located at the nodes. As a result, overfilling of the QDs located near the nodes may take place. This leads to the lasing generation of the other longitudinal modes (together with the main mode) with antinodes distinct from those of the first mode. A problem of the multi-mode generation is of first importance for the laser applications. A study of the physical processes controlling the multi-mode generation threshold is necessary to find the ways of suppressing the additional modes and to offer the proper design of single-mode operating lasers.

1 Processes controlling the spatial distributions of carriers

In QW or bulk lasers, diffusion in the active region will tend to smooth out the non-uniform carrier distributions and population inversion along the longitudinal direction, thus suppressing totally or partly the effect of spatial hole burning [4, 5].

In QD lasers, diffusion will play a similar yet minor role. The point is that the carriers, contributing to the stimulated emission, are those totally confined in QDs. There are also free carriers in the optical confinement layer (OCL) which contribute to the spontaneous emission, thus increasing the threshold current density. The free-carrier densities and the confined carrier level occupancies in QDs are coupled to each other by the rate balance equations. Due to this coupling, diffusion of free carriers should equalize to some extent the level occupancies in different QDs. Hence, two processes control the spatial distribution of free and confined carriers along the longitudinal direction. These processes are: the thermally excited escapes of the carriers from QDs to the continuous spectrum states and the diffusion of free carriers along the longitudinal direction.

The slowest process of the two above controls the carrier space distribution. In this work, the thermally excited escapes from QDs, rather than the diffusion, are shown to limit smoothing-out the carrier space distribution. There is an evident analogy to spatial hole burning in bulk lasers containing impurity centers in the active region [6, 7]. Non-vanishing values of the characteristic times of thermally excited escapes are shown to control the multi-mode generation threshold in QD lasers.

The following simple reasoning is worth presenting here. The fluxes of the thermally excited escapes of the electrons and holes from QDs are proportional to $f_{\mathrm{n,p}}N_{\mathrm{S}}/\tau^{\mathrm{g}}_{\mathrm{n,p}}$, where $f_{\mathrm{n,p}}$ are the mean electron and hole level occupancies in QDs, N_{S} is the surface density of QDs, $\tau^{\mathrm{g}}_{\mathrm{n,p}}$ are the characteristic times of thermally excited escapes of electrons and holes from QDs being given as [1]

$$\tau^{\mathrm{g}}_{\mathrm{n}} = \frac{1}{\gamma_{\mathrm{n}} n_1} = \frac{1}{\sigma_{\mathrm{n}} v_{\mathrm{n}} n_1} \qquad \tau^{\mathrm{g}}_{\mathrm{p}} = \frac{1}{\gamma_{\mathrm{p}} p_1} = \frac{1}{\sigma_{\mathrm{p}} v_{\mathrm{p}} p_1}. \tag{1}$$

Here $\gamma_{\mathrm{n,p}} = \sigma_{\mathrm{n,p}} v_{\mathrm{n,p}}$, $\sigma_{\mathrm{n,p}}$ are the cross sections of electron and hole capture into a QD, and $v_{\mathrm{n,p}}$ are the thermal velocities of electrons and holes. In Eq. (1), $n_1 = N_{\mathrm{c}}^{\mathrm{OCL}} \exp[-(\Delta E_{\mathrm{c}} - \varepsilon_{\mathrm{n}})/T]$ and $p_1 = N_{\mathrm{v}}^{\mathrm{OCL}} \exp[-(\Delta E_{\mathrm{v}} - \varepsilon_{\mathrm{p}})/T]$ where $N_{\mathrm{c,v}}^{\mathrm{OCL}} = 2(m_{\mathrm{c,v}}^{\mathrm{OCL}} T/2\pi\hbar^2)^{3/2}$ are the conduction and valence band effective densities of states for the OCL material, ΔE_{c} and ΔE_{v} are the conduction and valence band offsets at the QD–OCL heteroboundary, $\varepsilon_{\mathrm{n,p}}$ are the quantized energy levels of an electron and hole in a mean-sized QD (measured from the corresponding band edges), and the temperature T being measured in terms of energy.

The free-hole diffusion flux is proportional to $2kD_{\mathrm{p}}p$, where $p = p_1 f_{\mathrm{p}}/(1 - f_{\mathrm{p}})$ is the free-hole density [1, 2], $k = (2\pi/\lambda_0)\sqrt{\epsilon}$, λ_0 is the wavelength at the maximum gain, ϵ is the dielectric constant of the OCL, and D_{p} is the hole diffusion constant. Since D_{n} is greater than D_{p}, the free-electron diffusion is not the limiting factor.

The ratio of the hole escape flux to the diffusion one is $(1 - f_{\mathrm{p}})(N_{\mathrm{S}}\sigma_{\mathrm{p}} v_{\mathrm{p}})/(2kD_{\mathrm{p}})$. It is controlled by the cross section of hole capture into a QD and by the surface density of QDs. It is typically much less than unity. What this means is the process of thermally excited escapes is the slowest and hence the limiting one. Should this ratio be close to or greater than unity, both the processes above will control smoothing-out the spatial distribution of carriers. The multi-mode generation threshold in this case will be less than that in the case of small ratio.

2 Multi-mode generation threshold

An examination of the problem yields the following equation for the excess of injection (pump) current density over the threshold current density of the main (closest to the maximum of the gain spectrum) mode required for oscillating the next longitudinal mode:

$$\delta j = j_2 - j_{\mathrm{th}} = \frac{|\delta g|}{g^{\max}} \frac{eN_{\mathrm{S}}}{\dfrac{(1-f_{\mathrm{n}})}{\gamma_{\mathrm{n}} n_1} + \dfrac{(1-f_{\mathrm{p}})}{\gamma_{\mathrm{p}} p_1}} = \frac{|\delta g|}{g^{\max}} \frac{eN_{\mathrm{S}}}{\tau_{\mathrm{n}}^{\mathrm{g}}(1-f_{\mathrm{n}}) + \tau_{\mathrm{p}}^{\mathrm{g}}(1-f_{\mathrm{p}})} \tag{2}$$

where j_{th} and j_2 are the threshold current densities of the main and the next longitudinal modes, respectively, $g^{\max}$ is the gain spectrum maximum, and $f_{\mathrm{n,p}}$ are the mean electron and hole level occupancies in QDs required for the lasing of the main mode. The absolute value of the difference in the gain of the main and the next modes is

$$|\delta g| = \frac{1}{2}\left|\frac{\partial^2 g}{\partial E^2}\right| (\delta E)^2 = \frac{1}{2}\left|\frac{\partial^2 g}{\partial E^2}\right| \left(\hbar \frac{c}{\sqrt{\epsilon}} \frac{\pi}{L}\right)^2 \tag{3}$$

where the derivative is taken at $E = E_0$, E_0 is photon energy of the main mode, $\delta E = \hbar(c/\sqrt{\epsilon})(\pi/L)$ is the separation between the photon energies of the neighbouring modes ($\Delta m = \pm 1$), and L is the cavity length.

For Gaussian distribution of relative QD size fluctuations [1],

$$\frac{|\delta g|}{g^{\max}} = \frac{1}{2}\left(\frac{\hbar \dfrac{c}{\sqrt{\epsilon}} \dfrac{\pi}{L}}{(\Delta\varepsilon)_{\mathrm{inhom}}}\right)^2 \tag{4}$$

where $(\Delta\varepsilon)_{\mathrm{inhom}} = (q_{\mathrm{n}}\varepsilon_{\mathrm{n}} + q_{\mathrm{p}}\varepsilon_{\mathrm{p}})\delta$ is the inhomogeneous line broadening due to fluctuations in QD parameters (e.g., sizes), $q_{\mathrm{n,p}} = -(\partial \ln \varepsilon_{\mathrm{n,p}} / \partial \ln a)$ and δ is the root mean square (RMS) of relative QD parameter (size) fluctuations [1].

The threshold current density of the main mode is [1]–[3]

$$j_{\mathrm{th}} = \frac{eN_{\mathrm{S}}}{\tau_{\mathrm{QD}}} f_{\mathrm{n}} f_{\mathrm{p}} + ebBn_1p_1 \frac{f_{\mathrm{n}} f_{\mathrm{p}}}{(1-f_{\mathrm{n}})(1-f_{\mathrm{p}})} \tag{5}$$

where τ_{QD} is the radiative lifetime in QDs, b is the OCL thickness, and B is the radiative constant for the OCL.

The relative excess of injection current density over the threshold current density of the main mode required for oscillating the next longitudinal mode is

$$\frac{\delta j}{j_{\mathrm{th}}} = \frac{|\delta g|}{g^{\max}} \frac{\tau_{\mathrm{QD}}}{\tau_{\mathrm{n}}^{\mathrm{g}}(1-f_{\mathrm{n}}) + \tau_{\mathrm{p}}^{\mathrm{g}}(1-f_{\mathrm{p}})} \frac{1}{f_{\mathrm{n}} f_{\mathrm{p}} + \dfrac{\tau_{\mathrm{QD}}}{N_{\mathrm{S}}} bBn_1p_1 \dfrac{f_{\mathrm{n}} f_{\mathrm{p}}}{(1-f_{\mathrm{n}})(1-f_{\mathrm{p}})}}. \tag{6}$$

We shall restrict our consideration to the case of charge neutrality in QDs when

$$f_{\mathrm{n}} = f_{\mathrm{p}} = \frac{1}{2}\left(1 + \frac{N_{\mathrm{S}}^{\min}}{N_{\mathrm{S}}}\right) \tag{7}$$

where $N_{\mathrm{S}}^{\min} = (4/\xi)(\sqrt{\epsilon}/\lambda_0)^2 \tau_{\mathrm{QD}}\left((\Delta\varepsilon)_{\mathrm{inhom}}/\hbar\right)\beta\,(a/\Gamma)$ is the minimum surface density of QDs required to attain lasing at given losses β and inhomogeneous line broadening $(\Delta\varepsilon)_{\mathrm{inhom}}$ [1, 2], ξ is a numerical constant appearing in QD size distribution function, a is the mean size of QDs, and Γ is the optical confinement factor in a QD layer (along the transverse direction in the waveguide).

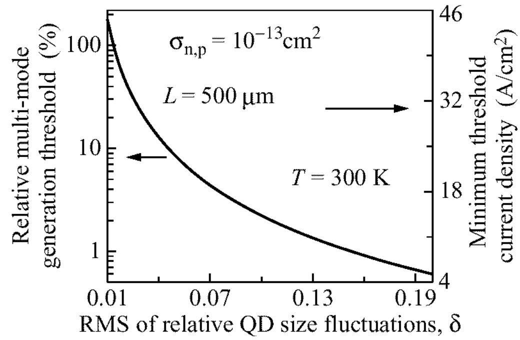

Fig 1. Relative multi-mode generation threshold and the minimum threshold current density of the main mode versus the RMS of relative QD size fluctuations δ.

3 Results and discussion

Analysis of (6) shows that, for the structure optimized at a given $(\Delta\varepsilon)_{\text{inhom}}$ (for which the threshold current density of the main mode is a minimum), $\delta j/j_{\text{th}} \propto [(\Delta\varepsilon)_{\text{inhom}}]^{-2}$ for small $(\Delta\varepsilon)_{\text{inhom}}$, and $\delta j/j_{\text{th}} \propto [(\Delta\varepsilon)_{\text{inhom}}]^{-7/4}$ for large $(\Delta\varepsilon)_{\text{inhom}}$.

As is easy to see from (1) and (6), $\delta j/j_{\text{th}}$ depends strongly on the cross sections of electron and hole capture into a QD, $\sigma_{\text{n,p}}$. Calculation of $\sigma_{\text{n,p}}$ is beyond the scope of the present article. Here, to estimate the multi-mode generation threshold, we take $\sigma_{\text{n,p}} = 10^{-13}$ cm^2 (which is much less than the geometrical cross section of a QD). At room temperature and at $L = 500$ μm, Fig. 1 shows the relative multi-mode generation threshold (the solid curve) and the minimum threshold current density of the main mode (the dashed curve) versus the RMS of relative QD size fluctuations δ. Each point on the curves corresponds to the specific structure optimized at the given δ. For the structures with $\delta = 0.05$ and 0.1, $\delta j/j_{\text{th}} \approx 8\,\%$ and $2\,\%$, respectively; the minimum threshold current density values are 14 and 25 A/cm^2, respectively. The inclusion of violation of the charge neutrality in QDs [2] will enhance the multi-mode generation threshold.

Thus an increase in the QD size dispersion not only increases the threshold current density but decreases the multi-mode generation threshold as well.

Acknowledgments

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